Subtropical cirrus cloud extinction to backscatter ratios measured by Raman Lidar during CAMEX-3

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[1] The NASA/GSFC Scanning Raman Lidar was stationed on Andros Island, Bahamas for the third Convection and Moisture Experiment (CAMEX 3) held in August–September, 1998 and acquired an extensive set of cirrus cloud measurements [*Whiteman et al.*, 2001]. Distinct differences in the optical properties of the clouds are found when the cirrus are hurricane-induced versus non-hurricane-induced. Hurricane-induced cirrus clouds are found to generally possess lower values of extinction-to-backscatter ratio (S) than non-hurricane-induced clouds. Comparison of the S measurements made here with those of other studies reveal at times large differences. Given that S is often a required parameter for space-based retrievals of cloud optical depth using backscatter lidar, these large differences in S measurements imply difficulties in developing a parameterization of S for use in space-based lidar retrievals. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 3360 Meteorology and Atmospheric Dynamics: Remote sensing. **Citation:** Whiteman, D. N., B. Demoz, and Z. Wang (2004), Subtropical cirrus cloud extinction to backscatter ratios measured by Raman Lidar during CAMEX-3, *Geophys. Res. Lett.*, *31*, L12105, doi:10.1029/2004GL020003.

1. Introduction

[2] Cirrus clouds affect the earth's radiation budget strongly by influencing both the greenhouse effect and planetary albedo [*Liou*, 1986] and can create errors in satellite retrievals. The study of *McFarquher et al.* [2000] showed that tropopause tropical cirrus clouds with optical depths of 0.01 have corresponding heating rates and cloud radiative forcing of 1.66 K day^{-1} and 1.6 W m^{-2}, respectively. Cloud climatology studies based on SAGE II observations [*Wang et al.*, 1996] have indicated frequencies of sub-visual cirrus (optical depths below $\sim$0.03) near the tropical tropopause of up to 70% indicating that the radiative effects of cirrus clouds are very large in tropical locations.

[3] Space-based lidar offers great potential for acquiring accurate global statistics on cloud heights and optical depths. However, due to the presence of multiple scattering and tropospheric aerosols, the retrieval of cirrus cloud optical depth from space-based lidar will under many circumstances require an accurate parameterization of the extinction-to-backscatter ratio for cirrus clouds. This parameterization may be a function of geographic location and/or cirrus type. Therefore, studies of the cirrus extinction-to-backscatter ratio are needed in differing geographic locations. Mid-latitude cirrus cloud properties have been extensively studied using lidar, cloud radar and radiometers [*Platt et al.*, 1987; *Mace et al.*, 2001; *Sassen and Comstock*, 2001; *Wang and Sassen*, 2002; *Sakai et al.*, 2003] but corresponding measurements in tropical or sub-tropical areas, where cirrus occurrences frequencies are high, are more limited [*Sassen et al.*, 2000; *Platt et al.*, 1998; *Comstock et al.*, 2002; *Immler and Schrems*, 2002] and none of those studies has made use of Raman scattering measurements.

2. Raman Lidar Measurements of Cirrus Clouds

[4] Raman Lidar systems have proven very useful at quantifying cirrus cloud optical depth and extinction-to-backscatter ratio [*Ansmann et al.*, 1992; *Reichardt et al.*, 2002; *Whiteman et al.*, 2001; *Sakai et al.*, 2003] even in the presence of multiple scattering [*Eloranta*, 1998; *Reichardt et al.*, 2000; *Whiteman et al.*, 2001]. The unique advantage of a lidar system that measures pure molecular scattering such as a Raman or High Spectral Resolution Lidar [*Eloranta*, 2000] is that the cirrus cloud extinction-to-backscatter ratio (S in units of sr) can be determined directly without the use of inversion [*Klett*, 1981]. To our knowledge the current work is the only study of cirrus cloud properties made in a sub-tropical or tropical location using either a Raman or High Spectral Resolution Lidar (HSRL).

3. The NASA/GSFC Scanning Raman Lidar (SRL) in CAMEX-3

[5] During July–September, 1998 the NASA/GSFC Scanning Raman Lidar (SRL) was stationed on Andros Island (24.7N, −77.75W) in the Bahamas as a part of the third Convection and Moisture Experiment (CAMEX-3). Though the main goal of the SRL participation in CAMEX-3 was to acquire detailed water vapor measurements during hurricane season, the system also provided high quality measurements of cirrus clouds. The cirrus cloud extinction-to-backscatter ratio derived from approximately 220 hours of SRL cloud measurements are studied here.

[6] The SRL is a mobile lidar system designed to detect light backscattered at the laser wavelength by molecules and aerosols as well as Raman-backscattered light from water vapor, nitrogen, and oxygen molecules. The measurements

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presented here were acquired using a XeF excimer laser (351 nm) with output power between 12–20 W, a 0.76 m telescope, a full-aperture scanning mirror and 2 photomultipliers for each sensed wavelength. More details on the Raman Lidar technique and on the configuration of the SRL at the time of the CAMEX-3 campaign are given by *Whiteman et al.* [1992, 2001] and *Whiteman and Melfi* [1999]. The SRL measurements analyzed here were acquired at night and ten-minute average quantities were used in the calculation of all data products.

4. Data Analysis Techniques

[7] Many of the techniques used to analyze the data are described fully by *Whiteman et al.* [2001] and *Whiteman* [2003a, 2003b] so only brief descriptions of data analysis techniques will be provided here. Cloud optical depth is calculated using a Beer's Law approach where the total attenuation of the Raman N_2 signal is considered between a lower and an upper reference altitude. As described by *Whiteman et al.* [2001], if the upper reference altitude for the attenuation calculation is chosen several kilometers above the cloud, the influence of multiple scattering is greatly reduced. Based on this previous study, if the cirrus cloud optical depth is less than 1 (~85% of the clouds studied here), the error in optical depth quantification due to multiple scattering should be less than 5%. The effect of multiple scattering on the quantification of the optical depth of the thicker cirrus clouds was studied here both with multiple scattering modeling [*Eloranta*, 1998; *Whiteman et al.*, 2001] and empirically by progressively increasing the upper reference altitude and re-calculating the optical depth. These studies indicated that the error in optical depth calculation for even the most dense cirrus clouds studied should be less than 10%.

[8] The cloud backscatter coefficient is calculated from the aerosol scattering ratio and the molecular backscatter coefficient as described by *Whiteman* [2003a, 2003b], Since this quantity is calculated using the ratio of lidar signals, the influence of multiple scattering on these calculations is minimal [*Wandinger*, 1998]. The layer-mean cirrus cloud extinction-to-backscatter ratio is then just the total optical depth divided by the integrated cirrus cloud backscatter coefficient. It should be mentioned that the errors that can be introduced in quantifying thin cirrus cloud backscatter coefficient due to the use of narrow spectral channels [*Whiteman*, 2003a, 2003b] are not present here due to the wide spectral channels used for these measurements (typically 6–8 nm) [*Whiteman et al.*, 1999].

5. Analysis of Cirrus Clouds Measured at Andros Island, Bahamas During CAMEX-3

[9] More than 350 hours of lidar measurements were analyzed for this study. Cirrus clouds were present in approximately 220 hours or 62% of the lidar data. Optical depths below 0.05 were measured 19% of the time. An optical depth of 0.05 is the value that has been established as the desired cirrus optical depth detection threshold for EOS sensors [*King*, 1999] but our previous cirrus investigations [*Whiteman et al.*, 2001] indicate, for example, that GOES satellite IR measurements are sensitive to the presence of cirrus with optical depth as low as 0.005. Furthermore, those same studies indicated approximately a 20% wet bias in the retrieval of total precipitable water from GOES if a cirrus cloud of 0.05 is undetected. In agreement with other studies, the cirrus cloud frequency results presented here imply that a large number of thin cirrus clouds are likely to go undetected by satellite potentially causing significant errors in satellite retrievals of water vapor, aerosols and other quantities.

[10] For the period of the CAMEX-3 experiment (August–September, 1998), a study of GOES (Geostationary Observational Environmental Satellite) IR imagery revealed that there were two main sources of cirrus cloud generation: 1) thunderstorms that originated in the general vicinity of Andros Island and 2) hurricanes that developed from disturbances off the coast of Africa and intensified as they traveled westward toward the Bahamas. In addition there was a small number of air-mass generated cirrus clouds. A total of approximately 40 hours of measurements of cirrus cloud analyzed as a part of this study were due to outflow from three hurricanes (Bonnie, Danielle, and Earl) during the periods of August 22–26, August 30 and September 2–3, respectively. (The GOES IR satellite loops for the entire CAMEX-3 experiment can be viewed at http://ramanlidar.gsfc.nasa.gov). The hurricane-induced and non-hurricane-induced cirrus clouds have been analyzed separately to study the influence of generating mechanism on cirrus properties.

6. Extinction-to-Backscatter (Lidar) Ratio, S

[11] The extinction-to-backscatter ratio, S, also known as the lidar ratio, is an important parameter that quantifies optical scattering properties of cirrus particles. It also is a required parameter for inversion of extinction or optical depth from backscatter lidar data if aerosol contamination or multiple scattering effects are present. In order to improve cirrus cloud optical depth retrievals from space-based lidar such as GLAS (Geosciences Laser Altimetry System) on ICESat (Ice, Cloud, and land Elevation Satellite - http://icesat.gsfc.nasa.gov/intro.html) or CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations - http://www-calipso.larc.nasa.gov/), where multiple scattering effects will be present, it is important to study the dependence of S on such variables as temperature, geographic location and cirrus generation mechanism.

[12] The cirrus cloud layer mean values of S for the CAMEX-3 hurricane and non-hurricane data were 19.0 ± 5.3 and 20.4 ± 7.5, respectively, indicating no significant difference in mean values depending on generating mechanism. However, when S is studied as a function of temperature, optical depth or cloud height differences between the hurricane and non-hurricane cases emerge. Figure 1 presents the cirrus cloud extinction-to-backscatter ratio as a function of mid-cloud temperature (a), optical depth (b) and cloud height (c). For all three comparisons, the non-hurricane-induced cirrus clouds possess consistently higher S values than the hurricane cases. Furthermore, the trend in S for decreasing temperature is quite different for these two subsets of the data. For the hurricane cases, S shows a general decrease from approximately 25 to 15 sr for temperatures decreasing from −50 to −70C. The

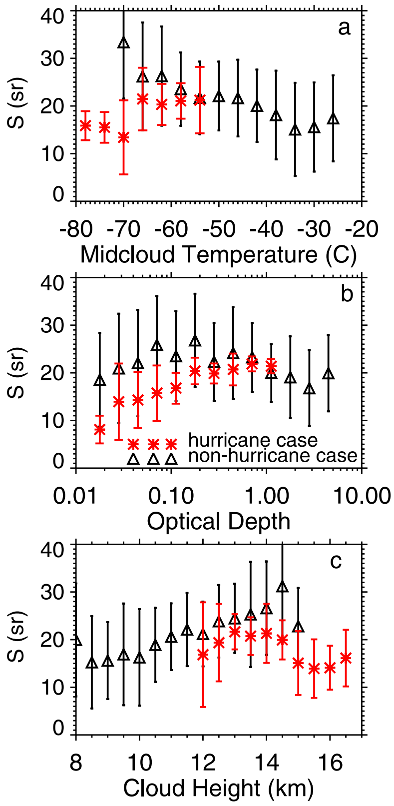

Figure 1. The dependence of S on mid-cloud temperature, optical depth and cloud height where the data have been segmented into hurricane and non-hurricane induced. The error bars represent the standard deviation of the data.

non-hurricane cases show a general increase in S values from approximately 25 to 35 over a similar temperature range. A general trend of S increasing with cloud height is seen in the non-hurricane data as well; a sensible result since temperatures tend to decrease with altitude. However, the S versus optical depth data show a similar trend of decreasing S for decreasing optical depth for optical depths below 0.2 in both the hurricane and non-hurricane cases.

[13] It is difficult to offer a definitive explanation for the consistent differences observed between the hurricane and non-hurricane S data at the same mid-cloud temperature, optical depth or cloud height. It would seem apparent however that these differences are related to the cirrus particle lifetime, where hurricane anvil outflows persist for days with a continuous supply of moisture allowing for an extended process of generation and regeneration of small ice crystals in a very cold region [cf. *Sassen et al.*, 2003]. The non-hurricane cases are generally due to more local sources with a shorter life cycle. How this difference in lifetime might explain the differences in the behavior of S for the two generating mechanisms shown in Figure 1 is not known at this time. Nonetheless, whatever the source of the differences in the measured S values from this CAMEX-3 dataset, the consistently lower values found in hurricane versus non-hurricane environments, for all methods of subdividing the data, imply that the mean extinction-to-backscatter ratios for cirrus clouds are strongly a function of the method of generation of the cirrus cloud.

[14] It is interesting to compare the values of S versus temperature measured here with others that have been published. *Reichardt et al.* [2002] studied the temperature and depolarization dependence of S for a selected set of arctic cirrus clouds. Mean S(T) values varied roughly between 10–30 sr in good agreement with the values presented here. Curiously, a decreasing trend in S values was observed for the coldest clouds that they studied much like the hurricane results shown in Figure 1a. The explanation for why S(T) for air-mass induced cirrus clouds in the arctic and hurricane-induced ones from the sub-tropics might have similar behavior at cold temperatures is not known at this time.

[15] Backscatter lidar studies of cirrus cloud S versus cloud temperature have also been made. *Del Guasta* [2001] studied S(T) for Antarctic cirrus clouds and showed a generally increasing value of S for decreasing cloud temperature; a trend that agrees with the non-hurricane clouds studied here although the magnitudes of their S values are approximately 50% higher than those presented here. *Chen et al.* [2002] studied cirrus clouds over Taiwan (25N, 121E), which is at a similar latitude to Andros Island (24.7 N). They show a relationship of S generally decreasing with temperature between −50 and −75C in agreement with our hurricane segmented data. Their values of S are in reasonable agreement with the non-hurricane data shown here near −70C, however at −50C their values are approximately 100% larger than those shown here. *Platt* [2002] have published a recent analysis of S(T) based on LIRAD (Lidar Radiometer) measurements of tropical cirrus clouds near the coast of Australia. Their results indicate S values increasing from approximately 40 to 100 sr as temperature decreases from −35 to −75C. The general increase in S with decreasing temperature agrees with our non-hurricane data, but the values in the Platt study are 2–3 times larger than the values presented here.

7. Summary and Conclusions

[16] The NASA GSFC Scanning Raman Lidar was stationed on Andros Island in the Bahamas during July–September, 1998 for the CAMEX-3 hurricane study program. To our knowledge, these measurements are the only Raman Lidar measurements of cirrus cloud extinction-to-backscatter ratio from a tropical or sub-tropical location and therefore contribute to the knowledge of the variation in this parameter as a function of location (sub-tropics) and season (summertime).

[17] The analysis presented here indicates that cirrus clouds occurred in 62% of the more than 350 hours of data analyzed. In addition, 19% of these cirrus clouds possessed optical depths below the EOS cloud detection threshold of 0.05. The dependencies of the cirrus cloud extinction-to-backscatter ratio (S) on temperature, cloud height and optical depth were studied for hurricane and non-hurricane cases. The values of S were consistently lower for the hurricane cases. Comparisons with other S(T) measurements were made indicating generally good agreement with a previous Raman Lidar study of *Reichardt et al.* [2002] but at times showing significant differences (~50%) with S(T) studies based on backscatter lidar [*Del Guasta*, 2001; *Chen et al.*, 2002] and very large differences (a factor of 2–3) with the LIRAD technique [*Platt*, 2002].

[18] Knowledge of the variation of S due to factors such as temperature, geographic location, and cirrus generation mechanism is needed to develop cirrus cloud optical depth retrieval algorithms from current and upcoming space-based lidar systems such as GLAS and CALIPSO, which under many circumstances will use backscatter measurements to infer cloud and aerosol optical depth through the use of an assumed extinction-to-backscatter ratio. The current study indicates that there is good general agreement between two Raman Lidar studies of cirrus cloud S values but that there are large disagreements among the other available studies of the temperature dependence of the cirrus cloud extinction-to-backscatter ratio, S. These results imply that large uncertainties likely exist in any parameterization of S(T) based on published data. Furthermore, the results presented here indicate that any parameterization should take into account the cirrus cloud generating mechanism to provide an accurate S value for an inversion of optical depth. Simultaneous measurements of cirrus cloud properties using various lidar techniques are called for to address the large differences in S values that have been found in this study and to work toward a more robust parameterization of S for use in space-based cloud optical depth retrievals.

[19] The analysis presented here should also be of interest to those involved in cirrus cloud studies from the Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment (CRYSTAL-FACE), which occurred in south Florida in July, 2002. One of the goals of CRYSTAL-FACE is to improve the ability of models to predict cirrus cloud optical and physical properties. However, the CRYSTAL-FACE dataset deals primarily with non-hurricane induced cirrus clouds. We have shown, though, that the method of cirrus generation can strongly influence the extinction-to-backscatter ratio of cirrus clouds. Given that the CRYSTAL-FACE follow-on field experiment is planned to occur in the tropics, where hurricane- generated cirrus clouds may be more likely to occur, the results presented here suggest that careful study and observation of the effect of generating mechanism on cirrus optical properties is needed.

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